# Cognitive Complexity and CAD Systems: Beyond the Drafting Board Metaphor

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**ABSTRACT**

*Computer-Aided Design (CAD) systems can and should support and enhance the product development process. Unfortunately, the benefits delivered by current systems have not met users' expectations. We believe that CAD systems should be designed to minimize the cognitive complexity facing the engineer; CAD systems should be easy to use and should help the engineer manage design-related complexity. A series of propositions are developed which refine these ideas.*

*To evaluate the central propositions, we constructed a prototype CAD system for the design of blanked and bent sheet metal parts . The user of the system is provided with a hand-held input device which interprets actions of the user's hands as production operations on a CAD representation of the part. The user creates sheet metal parts by bending, stretching, pushing, and moving the input device.*

*The system was demonstrated to engineers, engineering managers, and researchers, who provided ideas for future enhancements. Reactions to the demonstrations of the system have helped evaluate the concepts behind the system. Although we have used sheet metal as an example domain, we believe these ideas can be applied in a broad array of design contexts.*

## 1. Introduction

Computer-Aided Design (CAD) systems should support and enhance the product development process. Given the complexity of product development, this is a difficult task. Product development entails balancing many constraints, some of which may conflict. The complexity of the product development process leads to cognitive complexity for the engineer; the engineer must mentally juggle a large amount of important information. This cognitive complexity can lead to a situation in which important design factors are not considered and failures result. The consequences of such failures can be economically punishing or even tragic (such as the Kansas City Hyatt disaster [Petroski 1985]). Unfortunately, many of the currently available CAD systems do not reduce the complexity facing the engineer nor help the engineer manage that complexity. Indeed, because they are hard to use, many systems add to the complexity facing the engineer. Between the engineer's mental model of the design and the CAD representation of that design is the command syntax of the CAD system. This command syntax must be manipulated to create or modify a design. Yet for many systems, this command syntax is idiosyncratic and unintuitive, requiring a great deal of training and memorization to learn and use (CAD Report 1990).

Our central argument is that CAD systems should help minimize the cognitive complexity facing the engineer. More specifically, we argue that CAD systems should 1) assist in managing design-related complexity and 2) be easy to use. To accomplish this goal, we argue that CAD systems should:

- utilize a production-like design metaphor,
- evaluate designs with respect to the performance criteria,
- embed well understood geometrical constraints,
- automate well understood design tasks, and
- incorporate natural mappings in their controls and display.

To test our ideas, we have built a prototype CAD system for designing blanked and bent sheet metal parts. The user of the system is provided with a hand-held input device that interprets the three-dimensional actions of the hands in real time as production operations on a visual display of the part. Using the system, the user creates sheet metal parts by bending, stretching, pushing, and moving the input device.

In the four remaining sections of this paper, we provide background on engineering design and CAD systems technology, propose a set of ideal CAD system characteristics, describe a CAD system we ' ave built, and discuss the results and implications of our research.

## 2. Background: Product Development and CAD Systems

Design can be thought of as a multiple objective, constraint satisfaction problem. Typically, successful designs must achieve many diverse performance targets and satisfy competing constraints. For example, designing a gas turbine engine may involve meeting customer-specified performance criteria such as thrust, fuel consumption, cost, and weight. Individual engine parts may have design objectives and constraints such as:

- **Stiffness**. The part should be as rigid as possible.
- **Stress**. The part should not fail under the design load.
- **Temperature resistance**. The part should have satisfactory material properties at the operating temperature.
- **Geometry**. The part must attach to a specified interface and not interfere with adjacent parts.
- **Producibility**. The part should be producible, preferably on existing equipment.

Note that in general there is no overall objective function that allows one of the criteria to be traded off against another. For example, how much production cost is another unit of stiffness worth? Also note that some of the constraints are firm and can not be violated under any circumstances (for example, the stress on the part must never exceed the yield stress) while others are soft and can be violated if necessary (parts that cannot be made with existing production equipment can be supplied by a vendor).

Given the number and complexity of the criteria and constraints, the design process is usually one of satisficing (Simon 1981) rather than optimizing. Only rarely are designs optimized along more than one or two criteria. Rather, the usual process is to myopically improve the design with respect to one constraint, then iterate across the constraints until the design is satisfactory from all (see Calkins and Ishimaru [1984] for an example of this). Much of the justification for CAD system purchases is

based on potential improvements to the effectiveness of this design process, not just to the well-known efficiency gains in particular tasks that are enabled by CAD. Many design managers hope that CAD systems will enable changes in the design process that will make it less iterative, less myopic, and more productive.

## 2.1 CAD Systems Use

Many articles have detailed stories of large productivity benefits that have arisen from the application of CAD technology to engineering work. CAD systems have been shown to reduce design time (Fitzgerald 1987, Bull 1987, Teresko, 1988, 1990, Manji 1989, Frangini 1990), reduce design costs (Smith 1982, Dutton 1986, Fitzgerald 1987, Lansiaux 1987, Krouse et al. 1989), and improve design quality (Crombez 1988, Eade 1988, Vasilash 1988, DeMatthew 1989, Velloci and Childs 1990). Yet the literature also details stories of unmet expectations and daunting obstacles to successful deployment (Majchrzak and Salzman 1989). Systems that were expected to revolutionize the product development process delivered only meager improvements (Adler 1990). Problems have included software defects, slow learning curves, and complex user interfaces (Salzman 1989). Manager's opinions of the technology are quite mixed (Farrar 1987). Any review of the CAD literature leads to the conclusion that a number of ergonomic and organizational issues have hindered the successful deployment of CAD systems[1].

Note that most current CAD use is by drafters, not engineers (CAD Report 1990). This is true partially for historical reasons. Many companies have traditionally had a group of drafters serving a group of engineers; the engineer would sketch or otherwise specify the design geometry for the drafter, who would then produce a detailed drawing. But the continued use of CAD systems primarily by drafters is also due to the fact that CAD systems are difficult to learn and use. Engineers use CAD at most 25% of their time (CAD Report 1990). The memorization of CAD commands and syntax is so difficult that in many situations a CAD specialist (e.g. drafter) is needed to operate the system (CAD Report 1990). We believe that engineers could effectively use CAD systems much more than they do, but mastering the systems is currently too time-consuming a task for many engineers.

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[1] See, for example, the special issues of *IEEE Transactions on Engineering Management* devoted to CAD systems (August and November 1989).

We argue that the difficulties experienced in effectively deploying CAD technology are partially rooted in two major problems: CAD systems have historically been designed to support the drafting function, not engineering design. As such, most CAD systems are difficult to use for design. We are not the only researchers and system developers to have noticed these problems. Following is a review of some recent advances in CAD systems technology in these two problem areas.

**2.2 Advances in CAD Systems Technology: Supporting Engineering**

Several recent advances have allowed CAD systems to better support engineering work. We discuss three such advances: rule-based parametric design, integration of design and analysis packages, and feature-based design. Voelcker and his colleagues (1988) provide a comprehensive survey of these and related technologies.

The first of these, rule-based parametric design, allows the automated generation of part geometry for specific families of parts. Several CAD vendors have developed tools that allow engineers or tool developers to integrate geometric modeling commands with other types of problem-solving tools like object-oriented programming languages and rule-based systems. These tools have enabled the development of special-purpose tools for particular types of design tasks. For example, a firm that manufactures cutting tools may develop a CAD application that automatically produces a tool design from a specification of the required removal rate, geometric constraints, workpiece material, and coolant.

The second advance, better integration of design and analysis packages, lets the user quickly analyze the mechanical or thermal stresses on a part, as well as the kinematic behavior of a part. Improved interfaces between design and analysis packages make such analysis possible with the original part geometry and relatively little extra work. This allows the engineer to perform analyses on many more design variations.

Feature-based design provides the engineer with design primitives based upon part features such as holes, slots, bosses, or flanges. These primitives are typically composed of several lower-level geometric primitives and so increase the speed with which part geometry can be specified. The features are also easier to remember. Further, the features often correspond to manufacturing processes, so that the design of a part more closely matches the production of that part.

### 2.3 Advances in CAD Systems Technology: CAD Interfaces

There has been some research on improving the interface between the user and the CAD system. Pentland (1987) developed a sketching tool called "Super Sketch" which allows users to create visual images by deforming "parametric lumps of clay." The virtual lumps of clay are manipulated and deformed using a mouse to change slider bars. The user can perform Boolean operations on an arbitrary number of "lumps" to obtain the desired geometry.

Other research efforts have focused on input devices for CAD systems. The premise shared by these researchers is that creating and manipulating three-dimensional images requires three dimensional controls. Several teams have used the Polhemus 3Space input device[2]. This device uses low frequency magnetic waves to provide the three-dimensional position and orientation of a sensor relative to a stationary source. VPL Research in California has incorporated Polhemus devices in their "Eyephone" and "DataGlove" products[3]. The "Eyephone" is a head-mounted display device that provides the user with a stereoscopic view of a virtual world. The Polhemus sensor tracks 3-D head movements and enables the computer to match the viewer's position and orientation in the virtual world with their absolute position and orientation in the real world. The "DataGlove" is a glove worn on a user's hand that produces signals corresponding to the position of the user's wrist and the angles of each of the joints in the hand. When used together, the "Eyephone" and DataGlove" enable users to interact with a virtual world. It has been hypothesized that this kind of interface could be used in conjunction with a CAD system to manipulate three-dimensional objects.

Schmandt has incorporated a Polhemus sensor in a "Magic Wand" that is held in the user's hands like a pencil (Schmandt 1983). With his system a user can paint 3-D images in a virtual stereoscopic world that is projected into a space in front of the user by two monitors. Other systems which allow sketching and visualization in three dimensions are the 3-Draw (Roberts 1989) and the Interactive Graphics Workstation (Waldern et al. 1986) systems.

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[2] Polhemus, Inc., Colchester VT.

[3] VPL Research, Inc., Redwood City, CA.

Finally, NASA has developed the 3-D "Sensor Frame" input device that senses finger position and orientation in a volume in front of the computer monitor (NASA 1989). This device could be used as a CAD input device that allows designers to "sculpt" virtual parts simply by moving their hands.

## 3. Propositions for CAD System Design

Our goal for CAD system design is to minimize the cognitive complexity of engineering tasks. We suggested in the introduction that this complexity arises from the inherent properties of engineering design tasks as well as from the use of the CAD system itself. In this section we present the premises underlying our research, develop five propositions for CAD system design, and discuss the way each proposed characteristic influences task and system complexity.

Our first premise is that engineers need a tool to assist in creating part geometry. Humans have severely limited short term memory capacity (Miller 1956). This limitation contributes to the sequential and iterative nature of design and to the satisficing character of design solutions (Simon 1981). Designers would be unable to design even the simplest parts without some form of external working memory. This was true long before the advent of computers: drawings, sketches, and models have been used to facilitate design problem solving for centuries (McKim 1980).

Our second premise is that computers will be used to implement tools for defining part geometry. The external working memory required for design problem solving does not have to be stored, displayed, and manipulated by computer. (Many automobiles were designed with pencil and paper as recently as ten years ago, and some gas turbine engines are still designed on drafting boards.) Nevertheless, the need to transmit and distribute design data to many people, to store and reproduce designs, to evaluate and analyze designs using computer programs, and to incrementally edit designs make computers the likely vehicle for design support tools (Majchrzak and Salzman 1989).

Our final premise is that CAD systems will display images representing a three-dimensional view of the part. Researchers have shown that a system with a three-dimensional display (as opposed to several two-dimensional views) increases the performance of users carrying out tasks which require the perception and understanding of spatial information (Bemis et al. 1988). This is especially true

when the displays show surfaces, as surfaces are more easily interpreted than wire-frame images (Barfield et al. 1988).

### 3.1 CAD Systems Should Utilize a Production-Like Design Metaphor

The operating metaphor underlying a CAD system is defined by the choice of primitives and operations presented to the user. Historically, CAD systems have utilized the metaphor of the drafting board: drafters create part designs by manipulating lines and arcs in much the same way as they are manipulated with a pencil on a drafting board. There are several drawbacks to two-dimensional drafting with lines and arcs as a metaphor for constructing three-dimensional part geometry. One problem is the detail of the primitives; constructing a simple block with a hole through it may require dozens of lines and arcs. Another problem is that lines and arcs provide the designer with enough expressiveness to create parts that are not even physically realizable. Some commercial systems extend the drafting metaphor to three dimensions by allowing *wire-frame* images to be constructed with lines and arcs. These systems suffer many of the problems of two dimensional systems.

*Constructive solid geometry* modelers, which are designed around geometric primitives and Boolean operations on those primitives, provide the clear benefit of enforcing physical realizability. However, these modelers have some serious drawbacks for designing parts with complex curved surfaces (Pratt 1984, Computer Graphics World 1988).

We believe that CAD systems should utilize the metaphor of a production process. A CAD system designed around this metaphor utilizes commands that correspond to production-like operations. For example, when designing a machined part, the engineer would use a milling-like operation to create a slot (Cutkosky and Tenenbaum 1987). A strict production process metaphor is not appropriate for all types of parts, e.g. it is not clear that providing the engineer the capability of squirting liquid plastic would help design injection molded parts. In the case of net shape processes (e.g. casting, molding, or forging), the tooling fabrication processes may be more appropriate choices for design operations.

The production metaphor offers several advantages in both supporting design tasks and ease of use. Parts designed through a series of manufacturing-like operations are likely to be more producible than those designed through traditional CAD

systems, freeing the engineer from constantly assessing the production implications of the design. Designing a CAD system around a production metaphor will also make the systems easier to learn. The commands are more easily remembered, as they relate to physical operations such as mill, bend, and cut.

Both constructive solid geometry modelers and systems utilizing production process metaphors limit the geometrical expressiveness of the engineer. This limitation may in some cases be inconvenient. For example, when interpreted rigidly, this design paradigm would prevent designing a part by first constructing a cross-sectional view. We argue that this inconvenience is overshadowed by the advantages the metaphor provides.

### 3.2 CAD Systems Should Evaluate Designs

Successful part design requires satisfactory performance along many dimensions. For even the simplest bracket, the criteria include cost, weight, stiffness, strength, and geometric interference. Rather than requiring engineers to constantly evaluate designs with respect to the performance criteria, CAD systems should compute and display as much of this information as possible. We believe that engineers are good problem solvers if given adequate performance feedback on their designs. For example, when designing an inner body panel for an automobile, a designer could be presented with the number of required dies, the cost of the tooling, the cost of the material for the part, the number of welds required to attach the part to its neighboring parts, and the contribution of the part to the torsional and bending stiffness of the vehicle. This feature of CAD systems would serve primarily to ease the cognitive complexity facing the engineer. Evaluations of the design with respect to certain criteria would be made by the system, and would be easily available to the engineer.

### 3.3 CAD Systems Should Embed Well-Understood Constraints

Another way of reducing task complexity is to embed design constraints in the procedures of the CAD system. For example, if a pocket is being created in a block of material, the internal corner radii could be constrained to be greater than the minimum diameter end mill allowable for that operation. Similarly, holes could be constrained to be far enough away from a wall that the corresponding bolt head will fit. In the simplest implementation of this idea, the CAD system simply does not allow certain operations if they violate specified constraints. If the procedures of the

CAD system thereby limit the degrees-of-freedom available to the engineer, the engineer can focus more attention on other issues.

The idea of embedding well understood constraints in the CAD system is distinct from but compatible with the idea of designing the CAD system around a production metaphor. Many constraints that could be embedded are not related to production operations, or are related to a single company's production capability. For example, constraints on how close holes can be placed to the edge of a sheet metal part are different for laser-cut sheet metal than for blanked sheet metal. Thus a CAD system designed around a production metaphor should not enforce this constraint. The implementation of the CAD system at a certain company, however, may embed such constraints.

### 3.4 CAD Systems Should Automate Well Understood Design Tasks

Many commercial CAD packages provide programming languages that allow sequences of CAD commands to be chained together. In this way well understood design tasks can be automated. Rule-based parametric design systems allow the automatic generation of part geometry from a series of design rules and basic parameters. These design rules can include rules relating to material properties, weight and cost minimization, production process limitations, and other constraints. Automation of design tasks, however it is done, frees the engineer to concentrate on more critical design issues.

### 3.5 CAD Systems Should Incorporate Natural Mappings in their Controls and Display

There appear to be strong similarities between the cognitive and the physical manipulations of complex three-dimensional objects (Shepard and Metzler 1971, Shepard and Feng 1972). For example, if asked to compare two pictures of three-dimensional objects, a person will mentally "rotate" one of them in a manner analogous to the way one would rotate actual physical objects (Shepard and Metzler 1971). Humans also have well-developed hand-eye coordination because of a lifetime of experience of physically manipulating objects in the world. We believe that these characteristics of human perception and action should be manifest in CAD system design. In particular, we believe that there should be an isomorphism between the physical manipulation of the part as displayed by the CAD system and the spatial and tactile manipulations of a user's hands. We call this isomorphism a

*natural mapping*. For example, a natural mapping for rotating a displayed object would be to move a hand-held input device through a corresponding rotation in space. A natural mapping for elongating a displayed bar would be to stretch a hand-held object. Drilling a hole in a displayed part would be achieved by moving a hand-held *bit* through the desired trajectory. Controls structured in this fashion are much easier to learn and remember (Norman 1988), and thus free the user from the cognitive burdens imposed by some existing CAD systems.

## 4. The Prototype System

We built a prototype CAD system to test our key propositions. We chose blanked and bent sheet metal part design as a domain (an example part is shown in Figure 1). This choice was motivated by three factors: 1) sheet metal is an important and ubiquitous part process technology, 2) sheet metal parts exhibit some of the important problems associated with three dimensional part design, and 3) sheet metal part geometry is simple enough that we expected to be able to implement our ideas relatively easily. In this section we describe our prototype sheet metal CAD system (we will refer to it as *the system*).

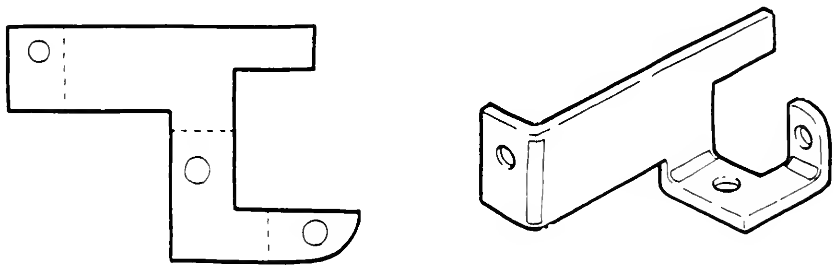

*Figure 1: Example blanked and bent sheet metal part*

The major idea behind the system is to invoke production-like design operations through spatial and tactile manipulations of a tool-like input device. In our system, the user literally bends, stretches, and moves the input device in space and sees a corresponding real-time modification to the sheet metal part displayed on the screen. For example, to create a bend, the user positions an image of the input device on the image of the part by moving the physical tool in space (much like a three dimensional cursor) and then bends the hand-held input device while a bend

is displayed in the image of the part on the screen. (We will call the image of the part the *virtual part* and the image of the input device the *virtual input device.*)

## 4.1 System Description

The system has two major components: a display screen and a tool-like input device, as shown in Figure 2. The display screen shows an image of the part to be designed. The input device (Figure 3) has three main components: the left body section, the right body section, and the hinge assembly. Each body section contains several momentary switches that enable users to select and perform desired design functions. The hinge assembly has two degrees of freedom: the two body sections may be either rotated or translated relative to one another.

*Figure 2: The Prototype System.*

The spatial position of the input device is relayed to the system software by a Polhemus 3Space sensor mounted in the right body half. This sensor measures the absolute position and orientation of the device in three dimensions. This

information is required by the design functions to map the virtual icon to the actual input device.

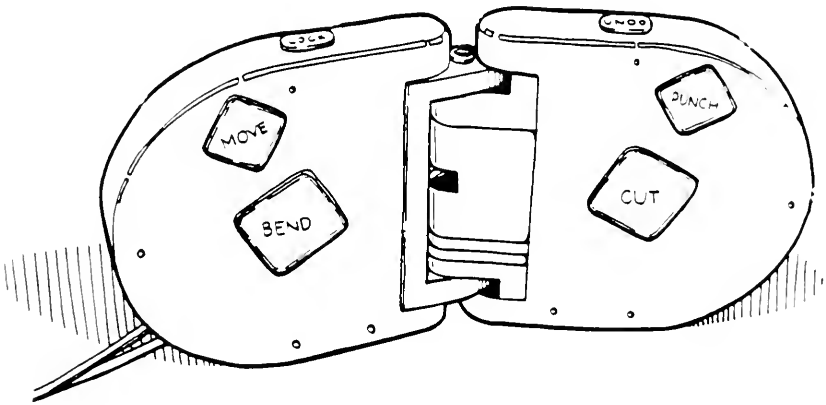


*Figure 3: The Input Device*

A small virtual input device icon, similar in shape to the actual input device, is shown on the virtual sheet metal piece. The icon is composed of two rectangles, which correspond to the two halves of the tool. This icon may be moved about the planes of the virtual material by the user. Operations are performed on the part at the position and orientation of this virtual icon.

The system allows engineers to create parts by performing various production-like operations on the virtual piece of sheet metal using the tool. Tactile and spatial inputs received from the device are interpreted as function commands by the system's software. The functions available to the user are:

- **Bend**: Pressing and holding the bend button on the input device and bending the two halves of the input device performs a bend in the sheet metal at the position and orientation of the virtual icon. The bend function is interactive; a change in the angle of the input device causes an associated change in the design representation. As the metal is bent, two physical constraints are

ensured: the given bend radius is implemented and the amount of material in the sheet of metal is conserved.

- **Stretch:** Pulling apart the two body halves causes new sheet material to be added along the axis determined by the virtual icon. This function finds all points of the sheet metal on one side of the virtual icon axis and moves those points in the same direction. The resulting change provides more than a simple stretch of metal. Using the Stretch and Shrink functions, practically any deformation which occurs in the plane of the sheet and does not change the number of edges and vertices can be accomplished.

- **Shrink**: Pushing the two body halves together causes sheet material to be removed along the virtual icon axis in a manner similar to the stretch function. Both stretch and shrink violate a strict production metaphor, but appear to be very useful. Both stretch and shrink are natural and intuitive operations on a sheet of metal.

- **Cut**: Pushing the cut button causes the icon to change to a red line anchored at the initial position of the icon. As the user moves the input device in space, the cut line moves around the screen, but remains anchored to the sheet metal. When the user releases the cut button, the cut is implemented. The cut has a width that is preset by the user.

- **Punch** (currently unimplemented): Pushing the punch button will cause a menu of punch outlines to appear on the screen. The user selects the desired outline and places the center point in the desired place. The punched hole can be moved interactively after initial placement.

- **Move**: Pressing and holding the move button allows users to move the virtual icon along the planes of the virtual sheet metal design. Movements and rotations in space are mapped to movements and rotations of the icon on the virtual sheet.

- **Lock**: Pressing the lock button "locks" the virtual sheet to the icon, so that rotation of the input device causes rotation of the virtual sheet. This feature

is selected often by users to help understand the three-dimensional shape of the part being designed.

- **Undo**: Pressing the undo button restores the geometry of the virtual design to the state preceding the most recently implemented function.

The system has been a vehicle for exploring our central research ideas, but there are many other features and functions that would be required before the system could be used to design parts in industrial practice. In particular, we have not implemented any way to 1) make curved cuts, 2) impose parametric values on the part dimensions, 3) add dimensional information to geometry, or 4) produce two-dimensional shop drawings from three-dimensional models. These features should be incorporated into our system if it is to be useful in an industrial setting.

## 5. Discussion

In this section we highlight what was learned from the construction of the prototype. We first discuss how efforts like these can be evaluated. We then present what we believe are the key features of the system. Finally, we propose a few directions for improvement.

### 5.1 Evaluating Prototype Systems

To evaluate the system, we demonstrated it to engineers, engineering managers, and researchers. Benchmarking against commercial CAD systems is inappropriate as the system lacks full CAD functionality. The demonstrations were valuable as they elicited insightful and sometimes surprising comments. The demonstrations thus provided a good early test of the system concept.

We plan to benchmark the system against commercial CAD systems in the future. We will use the information gained in the demonstrations to enhance the system and to develop hypotheses for benchmarking studies. Some of the key features of the system and some ideas for system enhancements that arose from the demonstrations are presented next.

### 5.2 Key Features of the System

The two major advantages of the system over existing alternative concepts are ease of use and part producibility. The system is easy to use. Although we have not

conducted any controlled experiments, we have observed that with one or two minutes of explanation, a novice user can create a producible sheet metal part design with the system. We attribute ease of use to the system metaphor and to the design of the input device. The system metaphor is of a production process. Bend, punch, and cut are directly analogous to the production operations for CNC sheet metal cutting combined with manual press brake bending. Stretch and shrink do not have common analogies for blanked and bent sheet metal parts, but they are intuitive physical operations. This metaphor makes remembering the system commands extremely simple and contributes to the ease of production of the resulting parts.

The design of the input device also makes the system easy to use. There are only a few operations that can be invoked by the user and they are all a combination of natural hand motions and visible button actions. Bending the input device results in bending the part, moving the hands results in movement of the virtual input device on the screen. Holding the cut button and moving the hands results in a cutting of the part. All of these actions are directly analogous to the way a real tool might be used to modify a real part and therefore are easy to remember and invoke. The undo feature further enhances usability.

The second major advantage of the system, part producibility, is ensured by both the production metaphor and by the production constraints. The production metaphor for design constrains the user to create physically realizable parts. There is no possible combination of commands that will result in a design with a face that is not closed or a line dangling in space. Production constraints also help to ensure that not only will the design be physically realizable, but that it can be made by the sheet metal process. The system imposes production constraints primarily in the bend function. When bending, the radius of the bend is specified by a program parameter. When the bend radius parameter is properly set, the user can not create a bend radius that is not realizable by the bending process. An additional constraint imposed by the system is that bends can not be made across an existing bend.

The goal of imposing part producibility was violated by the stretch and shrink functions. With these functions, it is possible to create a part that will not unfold to a flat sheet, e.g. a tab could be extended such that if unfolded it would overlap the rest of the part. We decided to include stretch and shrink to facilitate modification

of part dimensions at the expense of this potential problem. This could be addressed by automatically monitoring this condition and alerting the designer when the part can no longer be unfolded to a flat sheet.

### 5.3 Suggestions for Improvement

There are a number of ways in which the system can be improved. We will discuss sheet-metal-specific improvements here, but believe that the substance of the ideas applies to many design domains.

- **Intermediate part geometry:** Sheet metal parts are formed by blanking (cutting) then bending. Being able to perform operations on the unbent sheet metal part would facilitate the design activity. In effect this would allow the designer to view part geometry at an intermediate point in its production process. Operations performed on either the bent or unbent sheet would cause changes in both sheets. This feature, for any CAD system, would allow the user to evaluate constraints which apply to parts at different points of the production process.

- **Performance evaluation:** A cost model of the sheet metal production process would help the engineer make trade-offs between cutting and bending, or between scrap costs and bending costs. Other types of performance evaluation, like stress and weight, would also be useful.

- **Production constraints:** The system, as currently implemented, has some default values for design operation parameters. For example, a minimum bend radius is defined and can be changed for different types of sheet metal. Similarly, a default cut width has also been defined. Other default characteristics for other functions could be defined and incorporated into the system. For example, some manufacturing processes for sheet metal bending require a minimum distance between bends. This minimum distance could be set and violations flagged. The result is that the user automatically operates within design constraints and is made aware of violations as they occur.

  Another type of producibility constraint that might be useful is to impose parallelism and perpendicularity on cuts and bends. This would make parts

easier to produce. Since this constraint must often be violated in practice, this feature might be implemented as a user option.

- **Automation:** It may be possible to automate some aspects of sheet metal design, and use the system interface only for non-routine or other types of design not amenable to automation. For example, it is possible to automate the design of some types of sheet metal brackets by specifying the position, orientation, and shape of the interfaces of the bracket to other parts, as well as the other objects (such as other parts, tubes, cables, etc.) that the bracket must not intersect with. The system could automate the design of many of the simpler sheet metal brackets in a given design, and leave the more difficult brackets to the engineer.

## 6. Summary

Engineering design is complex work involving the juggling of a great deal of information, such as customer needs, process limitations, and material constraints. This can lead to a situation in which engineers are overwhelmed by design complexity and do not catch and correct design flaws. Economically punishing and even tragic failures can result.

We have argued that the complexity of design can be reduced by incorporating more design knowledge into the functionality of the CAD system and by reducing the complexity of CAD system operation. These goals can be achieved by utilizing a production-like design metaphor, by providing design evaluation, by embedding well understood constraints, by automating detailed design tasks, and by incorporating natural mappings into the CAD system controls and display.

We built a research prototype to test these ideas. We learned that the production metaphor and the ergonomics of our spatial-tactile input device combine to make the system very easy to learn and use. We believe that, in an industrial setting, constraints like those we placed on the bend operation can contribute to enhanced part producibility. Demonstrations of the prototype provided ideas for enhancements to the system.

Much could be done to further ease the cognitive burden on the engineer. More research and system development is needed to refine the design goals we have presented. It would also be valuable to apply these design goals in different contexts.

We believe that the resulting CAD systems will support the engineer more effectively, allowing a focus of attention on critical or creative design tasks.

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# Appendix

## System Description and Specifications

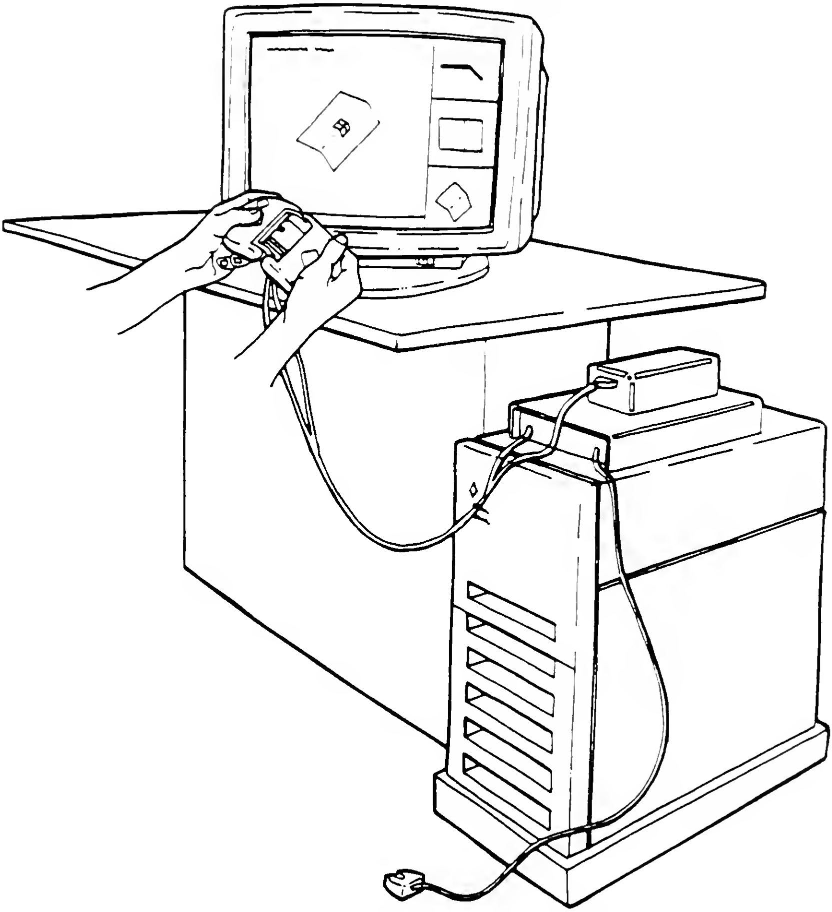

*Figure A: The Sheet Metal CAD System*

The system is shown in Figure A. Below, the software and hardware specifications of the system are described.

### Software

The system software is written in the C programming language using calls to SunPHIGS version 1.1

The system represents sheet metal using a full winged-edge data structure (Mantyla 1988). Sheet metal data is represented as vertices, edges connecting vertices, and faces composed of linked lists of edges.

### Hardware

The software runs on a Sun 4-330 SPARC workstation. This 32-bit RISC-based computer is equipped with a CXP hardware graphics accelerator using an 8-bit frame buffer.

A Polhemus 3Space Isotrak Sensor System[4] is embedded in the hand-held input device. This sensor transmits three-dimensional orientation and rotation information to the Sun computer's RS-232C serial port at 19200 baud.

Inputs from the push-buttons and the bend sensor potentiometer on the input device are delivered to the computer through a Data Translation 1414 Interface Board. This VMEBus board is equipped with a 12-bit analog-to-digital converter. The input device relays both analog and digital data to the computer through this board.

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[4] Polhemus, Inc., Colchester VT.

Date Due

JAN 1 7 1994